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Operational Implementation Design for the Earth System Prediction Capability (ESPC): A First-Look

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14. ABSTRACT

A general outline of the ESPC coupled atmosphere/ocean/ice/wave/land prediction system is proposed for the Initial Operational Capability targeted for 2018. A description of how it will cycle at both FNMOC and NAVOCEANO is included, although the specifics of how the distributed job control will function are still to be determined as the system becomes more mature. A potential issue with regard to the transfer of model output between the two centers has been identified and must be addressed in the upcoming years.

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1.0 Introduction

This document discusses the operational implementation of the Earth System Prediction Capability (ESPC) that will provide global environmental information to meet Navy and DoD operations and planning needs from under the sea to the upper atmosphere. It will be a fully coupled global atmosphere/ocean/ice/wave/land prediction system providing daily predictions out to 10 days and weekly predictions out to 30 days. The Initial Operational Capability (IOC) is targeted for 2018 at the Navy DoD Supercomputing Resource Center (DSRC).

At the time of this writing, the Navy DSRC has two identical (one) IBM iDataPlex supercomputers on the unclassified (classified) side with 1224 (252) compute nodes and 16 cores/nodes for a total of 19,584 (4032) cores per machine. Presently, Commander Naval Meteorology and Oceanography Command (CNMOC) receives 15% of the unclassified cycles (~130 Teraflops (TF), ~4400 cores) at the Navy DSRC for operational systems and ESPC will be required to fit within this allotment. They anticipate High Performance Computing Modernization Office (HPCMO) funded supercomputer upgrades such that the capacity will triple in FY14 (~400 TF, ~13,200 cores) and nearly tenfold by FY16 with an estimate of ~1000 TF (1 Petaflop (PF), ~33,000 cores).

2.0 ESPC component descriptions

The following sections describe the individual components of ESPC as they exist at the time of this writing. Figure 1 is a schematic of the existing uncoupled system and Figure 2 is the system flow.

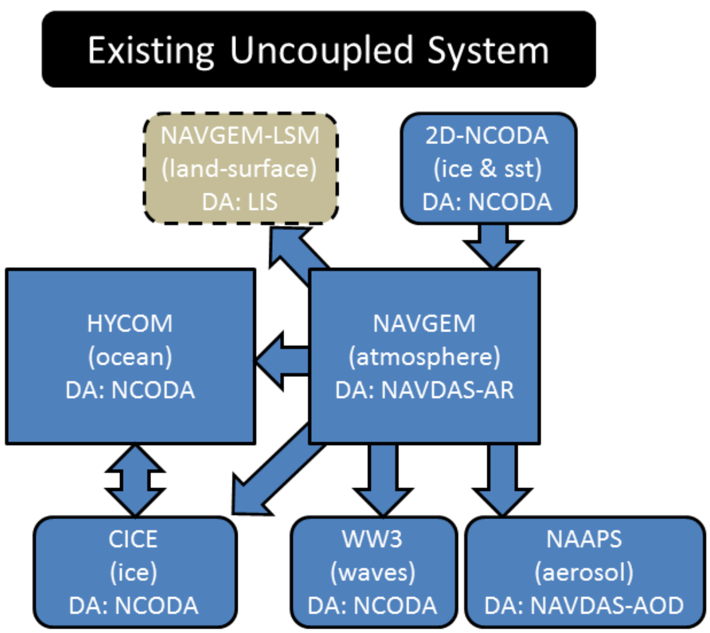

Figure 1: Schematic of the uncoupled system at the time of this writing. HYCOM and CICE are fully two-way coupled, but none of the other systems are. The component acronyms are defined throughout the text and DA = data assimilation. When the system is fully coupled, the 2D NCODA SST and ice analysis will no longer be needed as those fields will come from HYCOM and CICE, respectively.

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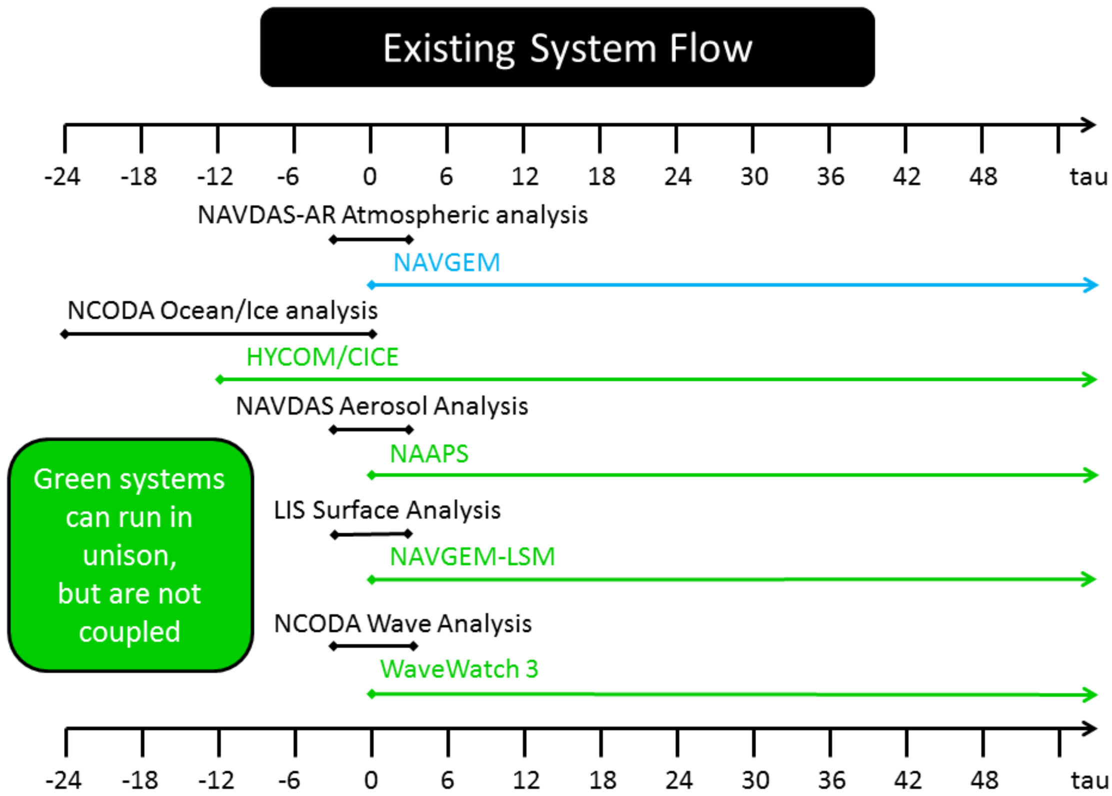

Figure 2: Schematic of the existing non-coupled system flow at the time of this writing.

2.1 NAVGEM – the atmospheric model

The NAVy Global Environmental Model (NAVGEM) version 1.1 was introduced as the U.S. Navy's operational global weather prediction system in 2013 and replaces the Navy Operational Global Atmospheric Prediction System (NOGAPS) which has been in operation since 1982. One of the major innovations of NAVGEM is the introduction of a Semi-Lagrangian/Semi-Implicit (SL/SI) dynamical core which allows for higher model resolutions without the need for smaller time steps. This initial NAVGEM operational transition has both higher horizontal (T359) and vertical resolutions than its predecessor, namely, 50 hybrid-sigma levels in the vertical and a horizontal resolution of approximately 37 km. Further, NAVGEM now includes cloud liquid water, cloud ice water, and ozone as fully predicted constituents, and an updated solar radiation and longwave-radiation parameterizations.

The SL dynamical core in NAVGEM finds the trajectory of the fluid motion that starts at the previous time step and ends up at the NAVGEM grid point location following Ritchie (1991). Integration by this method removes the Courant-Friedrichs-Lewy (CFL) limitation in conventional fixed point representations of the dynamical equations; however, high-speed gravity waves associated with high-frequency fluctuations in the wind divergence remain. This is mitigated by incorporating a SI method into the SL integration, where the terms responsible for the gravity waves are identified and treated in an implicit manner, thereby slowing down the fastest gravity waves. NAVGEM contains advection of cloud liquid water and cloud ice water, and a 2-species micro-physics cloud water parameterization based on the work of Zhao and Carr (1997).

Another significant improvement in NAVGEM is the addition of the Rapid Radiative Transfer Model for General Circulation Models (RRTMG) parameterizations for solar and longwave radiation, developed by the Atmospheric Environment Research Inc. (Pincus et al, 2003). RRTMG includes significantly more radiation frequency bands in the solar and longwave spectra than the previous NOGAPS radiation parameterizations and incorporates additional molecular absorbers and emitters. A unique feature of the RRTMG is the use of a Monte-Carlo technique to compute the sub-grid cloud variability and the vertical cloud overlap.

An official operational test (OPTEST) of NAVGEM 1.1 versus NOGAPS was conducted by Fleet Numerical Meteorology and Oceanography Center (FNMOC) for the period of 6 November 2012 – 18 December 2012 with a statistical evaluation based on FNMOC's standard global scorecard. This scorecard evaluates the comparative skill of the models based on anomaly correlation (AC), mean and root mean square errors of 16 different fields and observation types, including tropical cyclone tracks, 10-meter winds at buoy sites, 1000 hPa and 500 hPa AC, and winds and temperatures at radiosonde locations, assigning a weighted positive score to the model with statistically-significant better forecasts. Improvements in all cat egories would yield a skill score of +24. NAVGEM scored a +14, the highest score ever obtained for a global model transition at FNMOC. Historically, global model improvements resulted in a skill improvement of +2. NRL will continue to upgrade NAVGEM with planned transitions to higher vertical and horizontal resolutions, a more computationally efficient dynamical core, further improvements to the data assimilation system, more advanced physical parameterizations, and the assimilation of data from recently-launched satellite sensors.

Non-coupled NAVGEM 1.2 is now running operationally at Fleet Numerical Meteorology and Oceanography Center (FNMOC) and outputs spectral histories and variables on a native Gaussian grid out to 180-hours at 3-hourly intervals. Further, a series of IEEE binary fields are provided on a fixed latitude/longitude grid and fixed pressure levels in the vertical at both 0.5° and 1.0° resolutions containing fields such temperature, winds, moisture (in various units), geopotential height, surface fluxes and stresses as well as parameters such as convective and stratiform rainfall. For a single tau, this translates to approximately 135 GBytes every 6 hours.

2.1.1 GEFS – the ensemble forecast system

The FNMOC Global Ensemble Forecast System (GEFS) is produced in four steps: 1) take the NAVGEM high resolution analysis for the current update cycle and truncate it to the resolution used by the ensemble; 2) take the truncated analysis plus 80 6-hour lead time forecasts from the previous update cycle and make 80 perturbed versions of the analysis (i.e. ensemble members) using the ensemble transform (ET) technique; 3) run NAVGEM forecasts for each of the 80 ensemble members; and 4) generate ensemble products including gridded in binary (GRIB) files bundled for sending to the other NWP centers.

Eighty ensemble members are used in the ET to ensure adequate spread in the variations of the perturbations. The ET perturbations are computed over nine latitude bands to produce initial perturbations that resemble the geographic distribution of the NRL Atmospheric Variational Data Assimilation System – Accelerated Representer (NAVDAS-AR) analysis error estimate. Since a new high resolution analysis is produced every six hours, new perturbations are made every six hours so they include the latest observation and flow information.

Long forecasts to the 384-hour lead time are produced from 20 members for the 00Z and 12Z update cycles. Short forecasts to the 6-hour lead time are produced from the remaining 60 members for use by the ET in the next update cycle.

Forecast output consists of 1° by 1° spherical grids and is available through Come-And-Get-It-Product-Store (CAGIPS). In particular, for the variables, levels and forecast times specified by the North American Ensemble Forecast System (NAEFS), the grids are converted into GRIB files, bundled by ensemble member and forecast time, and sent to an ftp server that can be accessed by the National Weather Service and the Air Force Weather Agency (AFWA) in multi-model ensemble products. Graphics of ensemble mean, spread, and probabilities are produced for display on the NAVY Enterprise Portal-Oceanography (NEP-Oc). In addition, each member of the FNMOC WW3 wave forecast ensemble is driven by winds from a NAVGEM ensemble member. The NAVGEM forecast ensemble is also planned to be an integral part of the Hybrid NAVDAS-AR data assimilation system assisting by providing dynamic estimates of the error in the background forecasts.

2.1.2 NAVDAS-AR – the assimilation scheme

The NRL Atmospheric Variational Data Assimilation System – Accelerated Representer has been the operational assimilation system at FNMOC since 2009 and is a 4-Dimensional Variational (4D-Var) assimilation system capable of handling *in situ* and numerous remotely sensed meteorological data (Chua et al, 2009). Satellite observations account for more than 65% of the total assimilated observations in NAVGEM. NAVDAS-AR directly assimilates radiances from microwave radiometers and from interferometers and spectrometers in the infrared, and bending angle from Global Navigation Satellite Systems Radio Occultation Radio Occultation (GNSS-RO) profiles. Geostationary and Polar satellites also provide Atmospheric Motion Vector (AMV) information which is treated as an *in situ* observation. Some of the *in situ* data types include radiosondes, ships, stationary buoys, ACARS (Aircraft Communications Addressing and Reporting System), and AMDAR (Aircraft Meteorological Data Relay). Altogether over 20 million observations are processed, with an average of 2.2 million assimilated by NAVDAS-AR to provide an atmospheric analysis from which a new forecast cycle is begun. The default radiance bias correction method for NAVGEM/NAVDAS-AR is a variational bias correction approach, which estimates the bias predictors simultaneously with the atmospheric analysis during each data assimilation cycle (Dee, 2004). With variational bias correction the radiance bias corrections are constrained by the other observation types, the numerical weather prediction model, and the analysis procedure itself. NAVDAS-AR contains a tangent-linear and adjoint forecast model, which is at a reduced resolution compared to the full non-linear NAVGEM; as of 2013 this reduced resolution is approximately 100km. The observations are assimilated over a 6-hour time period 3-hours before and after the desired analysis time. This 6-hour period is further divided into 30-minute windows where the observations are assimilated and fit to model trajectories valid at these times.

2.1.3 The NAVGEM runstream

NAVGEM/NAVDAS-AR runs three times per update cycle (every 6 hours) at FNMOC. The preliminary run (at +1:30) generates boundary conditions for Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)/NAVDAS, while the 180-hour forecasts are initialized using the real-time analysis (at +3:00). Late in the 12-hr watch (around +8:00), a post-time NAVGEM/NAVDAS-AR run generates the background fields for the next 6-hr update cycle.

The NAVGEM/NAVDAS-AR systems presently run on the FNMOC A2 supercomputer. The NAVDAS-AR system runs on 90 processors in roughly 15 minutes while the 180-hour NAVGEM forecast at T359 spectral resolution (roughly 37km) and 50 vertical levels (model top ~80km), referred to as T359L50, completes in 50 minutes (running on 180 processors).

All Emerald compute nodes run RedHat Enterprise Linux 6.x Operating system, with 24G RAM/node. The nodes have two sockets which contain Intel Xeon Westmere (6 core) processors, but there is a mix of X5670 @ 2.93GHz and X5660 @ 2.80GHz.

2.2 HYCOM/CICE – the coupled ocean/ice models

Presently, the ocean and ice components are fully two-way coupled. These are the HYbrid Coordinate Ocean Model (HYCOM) and the Community Ice CodE (CICE), respectively.

HYCOM is a primitive equation ocean general circulation model capable of nowcasting and forecasting the 3-dimensional temperature, salinity and current structure of the global ocean. Its grid is uniform cylindrical from 78.64ºS to 66.0ºS , on a Mercator projection from 66.0ºS to 47ºN and curvi-linear north of this as it employs an Arctic dipole patch where the poles are shifted over land to avoid a singularity at the North Pole. It employs potential density referenced to 2000 m and includes the effects of thermobaricity (Chassignet et al., 2003). Vertical coordinates can be isopycnals (density tracking), often the best coordinate in the deep stratified ocean, levels of equal pressure (nearly fixed depths), best used in the mixed layer and unstratified ocean and sigma-levels (terrain-following), often the best choice in shallow water. HYCOM combines all three approaches by choosing the optimal distribution at every time step. The model makes a dynamically smooth transition between coordinate types by using the layered continuity equation. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow coastal seas and unstratified parts of the world ocean. It maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics. HYCOM is configured with options for a variety of mixed layer submodels (Halliwell, 2004). A more complete description of HYCOM physics can be found in Bleck (2002) and an application of global HYCOM within the Indonesian Sea can be found in Metzger et al. (2010). Two validation test reports (Metzger et al., 2008; 2010b) describe the verification that led to it being declared an operational system.

HYCOM uses NAVGEM forcing that includes these fields: air temperature at 2 m, specific humidity at 2 m, net surface shortwave and longwave radiation, total (large scale plus convective) precipitation, ground/sea temperature, zonal and meridional wind velocities at 10 m, mean sea level pressure and dewpoint temperature at 2 m. The first six fields are input directly into the ocean model or used in calculating components of the heat and buoyancy fluxes while the last four are used to compute surface wind stress with temperature and humidity based stability dependence.

HYCOM outputs whole domain, 3-dimensional archive files on its hybrid vertical grid. These can be a daily average, or an instantaneous snapshot at a user-defined frequency. Currently, the 3-hourly native grid snapshots are further interpolated in space to a uniform 0.08° latitude/longitude grid between ±80° latitude and in the vertical to 40 pre-defined Naval Oceanographic Office (NAVOCEANO) z-levels for the following variables: sea surface height (SSH), temperature, salinity, zonal and meridional velocity components, and these are output in netCDF format. For a single tau, this translates to approximately 2.9 GBytes.

The Los Alamos-developed CICE model (Hunke and Lipscomb, 2008) is two-way coupled to HYCOM via the Earth System Modeling Framework (ESMF) (Hill et al., 2004). The sea ice and ocean models use the same grid configuration and pass information back and forth every hour. CICE includes sophisticated ice thermodynamics such as multiple ice thickness layers, multiple snow layers and the capability to forecast multi-categories of ice thickness according to World Meteorological Organization definitions. In addition, CICE has several interacting components including a thermodynamic model that computes local growth rates of snow and ice due to snowfall; vertical conductive, radiative and turbulent fluxes; a model of ice dynamics that predicts the velocity field of the ice pack based on a model of the material strength of the ice; a transport model that describes advection of the areal concentration, ice volumes and other state variables; and a ridging parameterization that transfers ice among thickness categories based on energetic balances and rates of strains.

The input forcing is the same as HYCOM, with the exception that CICE requires the downward components of the surface radiative fluxes rather than the net values currently used by HYCOM. CICE outputs instantaneous snapshots of 41 ice (ice concentration, thickness, velocity), ocean (surface temperature, salinity, velocity), and atmosphere (temperature, radiation) variables. A single tau is approximately 2.7 Gbytes.

2.2.1 NCODA – the ocean/ice assimilation scheme

The Navy Coupled Ocean Data Assimilation (NCODA) is a fully three-dimensional, multivariate (3DVar) data assimilation scheme (Cummings, 2005; Cummings and Smedstad, 2013) for the following ocean/ice variables: temperature, salinity, geopotential, vector velocity components, and ice concentration; all are analyzed simultaneously. Data are selected for assimilation based on receipt time (the time the observation is received at the center) instead of the observation time so, any data received since the previous NCODA analysis are used in the next analysis. For each data type the user defines the maximum age of data to be used in the analysis. All data will not necessarily be synoptic and so they are compared against a time dependent background field using the First Guess at Appropriate Time (FGAT). Hourly forecast fields are used in FGAT for assimilation of SST to maintain the diurnal cycle, whereas daily averaged forecast fields are used in FGAT for profile data type, both synthetic and real. NCODA can be run in stand-alone mode but here is cycled with HYCOM and CICE to provide updated initial conditions for the next model forecast using an incremental analysis update procedure (Bloom et al, 1996). Currently the NCODA ocean analysis increments are inserted into HYCOM over a six hour window whereas the NCODA ice analysis is directly inserted into CICE. Corrections to the HYCOM and CICE forecasts are based on all observations that have become available since the last analysis. These include surface observations from satellites, including altimeter SSH anomalies, sea surface temperature (SST), and sea ice concentration, plus *in situ* SST observations from ships and buoys as well as temperature and salinity profile data from XBTs, CTDs and Argo floats. See Table 13.1 in Cummings and Smedstad (2013) for a complete list of assimilated observations along with typical data counts. All observations must be quality controlled and this is done via NCODA_QC (Quality Control) which is operational at NAVOCEANO. By combining these various observational data types via data assimilation and using the dynamical interpolation skill of the model, the 3-D ocean environment can be more accurately nowcast and forecast.

2.2.2 The HYCOM/CICE runstream

The HYCOM/CICE runstream starts with the NCODA analysis (performed once per day) at tau = -12 hours with a ±12 hour data window. After the NCODA analysis, HYCOM is run forward with the analysis incrementally inserted into the ocean model over the first six hours, thus at tau = -6 HYCOM has fully ingested all the observational data. HYCOM and CICE continue to run in forecast mode out to 180 hours. If for some reason the NAVGEM atmospheric forecast is shorter than this, the last forecast time point is slowly blended toward climatological forcing to complete the 180 hour forecast time period. The existing 1/12° system runs on 900 IBM iDataPlex cores and takes ~1.0 wall hour for a complete day, ~45 minutes for the NCODA analysis and ~15 minutes for HYCOM/CICE. We currently anticipate the 1/25° system will run on 4800 cores and take ~1.5 wall hours for a complete day, ~60 minutes for the NCODA analysis and ~30 minutes for HYCOM/CICE, although these numbers are subject to change because efforts are underway to parallelize aspects of NCODA's data preparation software.

2.3 WAVEWATCH III™ – the wave model

WAVEWATCH III™ (WW3) (Tolman, 2002, 2007) is a third-generation wave model developed at NOAA/NCEP which employs a third-order numerical propagation scheme in order to control numerical diffusion of swell. The wave growth and dissipation source terms allow more rapid wave growth under the influence of strong wind forcing than in previous wave models.

WW3 solves the spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of these equations is that the wind field, water depth and surface current field vary on time and space scales that are much larger than the corresponding scales of a single wave. Furthermore, the propagation scheme used by the model is conditionally stable, which means that the model becomes inefficient with resolution finer than O(1 km).

The computational grid is typically on a latitude-longitude (spherical) mesh, where energy at each grid point is represented on discrete directions and frequency bins. Curvilinear grids have been introduced in the latest versions of the model which include a tested domain covering the Arctic region. This latter domain will be included to function together with the traditional latitude-longitude meshes in the multi-grid system described below.

2.3.1 Multi-grid model description

The multi-grid model which has been validated (Chawla et al., 2009; Rogers et al., 2012) allows for the two-way communication of energy across domain boundaries. Typically, as it was with older versions of WW3, a host model passes wave energy through the boundary to a nest domain and whatever happens within the nest domain does not affect the host grid. This can have the effect of not allowing the computational results with significant events of a high resolution model—potentially using better winds and better bathymetry—to be shared with the host and other regions.

An advantage to running the multi-grid version of WW3 is that the domain configuration is more efficient, using computational resources more where it is needed, i.e. minimizing the redundant use of computational resources. With older model versions, the model computed for all water points in the host domain regardless of whether these points were already covered by a nest. Now, the nest domain points are mutually exclusive from others except where there is overlap within the buffer zone around the boundaries. In addition, it is possible run together domains with different grid types (specifically curvilinear grids vs. regular grids) passing wave energy across the boundaries in both directions (Rogers and Campbell, 2009).

As the name implies, the multi-grid system runs multiple domains altogether instead of the traditional approach of running individual domains and passing boundary condition information to nest domains and running those separately. Since everything is together, the model set up is less tedious obviating the need to specify individual points in the host domain about the nest to which information is to be shared. One-way nesting is accommodated with the passing of boundary conditions of spectral points for domains used by WW3 or other wave models such as SWAN (Similating WAves Nearshore) (Booij et al., 1999), which is used for nearshore domains.

2.3.2 Operational Implementation

WW3 is run operationally at FNMOC (Wittmann, 2002; Jensen, 2002) and is currently in transition to operations at NAVOCEANO (Rogers and Dykes, 2012; Dykes and Rogers 2013). This latter reference provides details on the operational implementation at NAVOCEANO. At both centers, the systems are fully automatic. The multi-grid system is to be implemented at NAVOCEANO but not at FNMOC due to the different purposes for running the model at each of these centers. FNMOC wave forecasts are continually issued for global and large regional domains, whereas NAVOCEANO provides sea state dependent littoral products and services for short term support.

As soon as they are available, wind fields from FNMOC are processed to force the wave model. The availability of the modeled wind fields is the primary factor that governs when any wave model can begin to run in any cycle. The regional wave model domains can use the 10-meter zonal and meridional velocity components of wind normally at three-hour intervals from COAMPS (Hodur, 1997) taking advantage of mesoscale dynamics. Otherwise winds from NOGAPS and NAVGEM can be used for all domains. In the multi-grid case all the wind fields from various meteorological models must be available or substituted with other appropriate fields before the multi-grid system can start.

On domains where it applies, ice concentrations from CICE provide inputs to the wave model. Since, the ice field does not change significantly from one day to the next, it is not so critical to update the ice field daily in larger domains. Although not applied at this time, ocean surface zonal and meridional components of currents can also be input into the wave model.

Restart files are used to maintain continuity between cycles. No model run for a cycle can start without either having a restart from a previous run, or by using a cold start (i.e. re-initializing with artificial conditions). In the case of a multi-grid configuration, all the restarts in the system are made and used in tandem. For any one domain to be removed from the system a cold start must be implemented for all domains to continue, otherwise a void is left which the system cannot handle. Adding domains on the other hand can be done on the fly, since the energy of the original space over which the new domain is occupying is easily replaced with a cold start with reasonable values for that domain.

The wave model is run every 12 hours forecasting to as long as 180 hours at intervals available as fine as hourly. The existing multi-grid system at NAVOCEANO runs on 128 IBM iDataPlex cores and a 48-hour forecast runs takes approximately 22 minutes of wall clock time. FNMOC's global-only domain at 0.5 degrees grid spacing for a 96 hour forecast running on 32 processors on a Nehalem cluster takes about 7 minutes. We currently estimate that a global domain at 1/8° for a 96-hour forecast can take up to 5 hours.

All models undergo pre- and post-processing with regards to the model run. This processing involves preparing the input data for the model run and taking the model output and converting it into other formats such as netCDF. For the multi-grid system, each individual domain can be processed before and after as if they were individual model runs. Field outputs are bulk parameters calculated from the energy spectra and include significant wave height (SWH), mean and peak wave direction, mean and peak period, and wind waves. Point output of the spectral energy and bulk parameters are also available and in fact the spectra are the source of boundary conditions for the SWAN models run at NAVOCEANO.

2.3.3 WAVEWATCH III™ - data assimilation

The WW3 wave model assimilation capability has been integrated into the NCODA system and has been applied at FNMOC (Wittmann and Cummings, 2004), but not at NAVOCEANO. A draft validation test report has been written but not yet published.

The NCODA assimilation is a 3D-Var technique and is applied in a sequential incremental update cycle. All altimeter SWH observations falling within a 6-hr time window are used in the analysis. The analysis background, or first guess, SWH field is generated from a 6-hr wave model forecast. The corrections are computed from the SWH observations and added to the model forecast to produce a corrected SWH analysis field. The full wave model spectrum is then updated from the corrected SWH analysis field by adjusting the model spectrum at each grid point with a scaling factor, such that the forecast SWH matches the analyzed SWH from the altimeter measurements. There is no dependence on the directions of energy in the spectra.

2.4 NAVGEM-LSM – the land/surface model

Currently the NAVGEM- Land Surface Model (LSM) is a simple 1-D NRL developed column model containing 4 bulk soil layers described by their water and ice content and their temperature. The vegetation cover information is parameterized from the USGS data base and contains prognostic variables of canopy temperature and canopy water content. Finally for snow covered ground a snow temperature is also specified.

A second option to the NRL developed LSM is the community Noah Land Surface Model (Mitchell, 2005). The Noah LSM has been incorporated in NAVGEM but is not the LSM currently operational in NAVGEM at FNMOC. Noah is a stand-alone, 1-D column model which can be executed in either coupled or uncoupled mode. The model applies finite-difference spatial discretization methods and a Crank-Nicholson time-integration scheme to numerically integrate the governing equations of the physical processes of the soil-vegetation-snowpack medium. Noah has been used operationally in National Center for Environmental Prediction (NCEP) models since 1996, and it continues to benefit from a steady progression of improvements.

2.4.1 LIS – the land surface assimilation scheme

Incorporation of the Land Information System (LIS) and its data assimilation component is currently under development within the NAVGEM/NAVDAS-AR framework. The object oriented framework of LIS allows for a direct interaction with the NAVGEM/NAVDAS-AR systems. Full documentation of the LIS system is available at (http://lis.gsfc.nasa.gov).

LIS is a flexible land surface modeling and data assimilation framework developed with the goal of integrating satellite- and ground-based observational data products and advanced land surface modeling techniques to produce optimal fields of land surface states and fluxes. The LIS infrastructure provides the modeling tools to integrate these observations with the model forecasts to generate improved estimates of land surface conditions such as soil moisture, evaporation, snow pack, and runoff, at 1 km and finer spatial resolutions and at one-hour and finer temporal resolutions.

The fine scale spatial modeling capability of LIS allows it take advantage of Earth Observing System (EOS)-era observations, such as Moderate Resolution Imaging Spectroradiometer (MODIS) leaf area index, snow cover, and surface temperature, at their full native resolution. LIS features a high performance and flexible design, provides infrastructure for data integration and assimilation, and operates on an ensemble of land surface models for extension over user-specified regional or global domains. LIS is designed using advanced software engineering principles to enable the reuse and community sharing of modeling tools, data resources, and assimilation algorithms.

The system is designed as an object-oriented framework, with abstractions defined for customization and extension to different applications. These extensible interfaces allow the incorporation of new domains, land surface models (LSMs), land surface parameters, meteorological inputs, data assimilation and optimization algorithms. The extensible nature of these interfaces and the component style specification of the system allow rapid prototyping and development of new applications. These features enable LIS to serve as both:

• Problem Solving Environment (PSE) for hydrologic research to enable accurate global water and energy cycle predictions.

• Decision Support System (DSS) to generate useful information for application areas including disaster management, water resources management, agricultural management, numerical weather prediction, air quality and military mobility assessment.

2.4.2 The NAVGEM-LSM runstream

The current NAVGEM-LSM does not contain a data assimilation component. Efforts to couple the NAVGEM-LSM with LIS have begun. The first step is to spin-up the LIS system with NAVGEM-LSM initial conditions over a long period typically 1-year. Once completed the LIS system is initialized by the NAVGEM-LSM and NAVGEM atmospheric state after a NAVDAS-AR update cycle. The LIS data assimilation step creates an analysis which can be used for NAVGEM and NAVGEM-LSM forecast used for the subsequent update cycle. In this scenario until the data assimilation components are coupled the initial conditions provided by FNMOC to NAVOCEANO will contain NAVGEM-LSM forecasts.

2.5 NAAPS – the aerosol model

The Navy Aerosol Analysis and Prediction System (NAAPS) is the U.S. Navy's global operational aerosol, air quality and visibility forecast model that generates operational, six-day, forecasts of aerosol conditions worldwide. NRL has developed, tested, and transitioned NAAPS to operations at

FNMOC for forecasting the concentration of the dominant atmospheric aerosols and the subsequent effects on visibility for the entire globe. The six-day forecasts of sulfate, dust, smoke and salt aerosol particles are used by a wide range of DoD users, including weather forecasters, mission planners, operators, and scientists, as well as non-DoD users. With this model, we are now able to predict the concentration of the dominant visibility reducing aerosol species up to six days in advance anywhere on the globe. NAAPS is particularly useful for forecasts of dust storms downwind of the large deserts of the world: Sea of Japan and China Sea, Mediterranean Sea, and the tropical Atlantic Ocean. NAAPS also accurately predicts the fate of large-scale smoke plumes originating from boreal and tropical forests and the savannah.

The Fire Locating and Modeling of Burning Emissions (FLAMBÉ) database for biomass burning is used operationally to describe the hourly smoke emissions for NAAPS. The FLAMBÉ project (Reid et. al., 2004) successfully monitors fire activity and smoke transport for the globe. Half-hourly GOES-8/-10 Wildfire Automated Biomass Burning Algorithm (WF_ABBA) fire products for the Western Hemisphere have been produced at the University of Wisconsin-Madison and implemented in smoke source functions for NAAPS. FLAMBÉ incorporates MODIS fire products from the University of Maryland in near real time. This data is incorporated into a smoke flux scheme for the Eastern Hemisphere thus allowing NAAPS to utilize a global smoke source function. FLAMBE has been successfully transitioned to operations at FNMOC.

The forecasts of aerosol concentration are distributed via classified and unclassified networks for use by DoD forecasters, operators, planners, and aviators. NRL has also transitioned an associated model (Forecast of Atmospheric and Optical Radiative Properties) that calculates the fundamental optical properties of the different aerosol species at wavelengths of interest to DoD for Electro-Optic (EO) propagation calculations. These properties are used by the Target Acquisition Weapons Software (TAWS) to calculate slant-path visibility. Previous to NAAPS, the user chose the aerosol load based on local conditions and had to input the aerosol information by hand. Now the aerosol conditions at any point in the world up to six days in the future are automatically available for use in TAWS. In another application, the forecasts are used to screen satellite retrievals of sea surface temperature (SST) for dust contamination by NAVO, thus improving hurricane forecasts.

2.5.1 NAVDAS-AOD – the aerosol assimilation scheme

NAVDAS for Aerosol Optical Depth (AOD) is comprised of data quality control and analysis elements. It applies the two-dimensional variational (2D-Var) analysis technique to quality assured MODIS MOD04 aerosol optical depth product that has been subjected to QC, QA, bias correction and cloud screening. Four major steps are included in the NAVDAS-AOD process: (1) Convert NAAPS mass concentration to τ bλ (3-D to 2-D conversion); (2) run NAVDAS 2D-VAR to create a new analysis field τaλ from τ bλ and τ oλ; (3) improve the NAAPS mass concentration field using τaλ (2-D to 3-D conversion); and (4) use the new mass concentration field as an initial condition for the next 6-hour NAAPS run. The system is described in Hyer et al. (2011), Zhang et al. (2005), Zhang et al. (2008) and Zhang and Reid (2006).

2.5.2 The NAAPS runstream

The input satellite data for NAVDAS-AOD have a latency of 6 hours and are not available for analysis at the tau = 0 analysis time. Instead, an analysis is produced at tau = -6 using MODIS MOD04 data for the window of tau = -9 to tau = -3. The 6-hour NAAPS forecast valid at tau = -6 is used as the first guess. This new tau = -6 analysis is used to initialize a short 6-hour NAAPS forecast to produce the apparent tau = 0 initial condition that is used to initialize the long 144 hour forecast. MODIS fire detection data from the previous 24 hours are used to prescribe the smoke emissions for the 144 hour NAAPS forecast. The entire NAAPS suite is completed in less than 90 minutes using 12 processors.

3.0 The future ESPC coupled system

A schematic of the future ESPC coupled system is shown in Figure 3. Two-way coupling will exist between most systems, however there are some exceptions. Presently, NAVGEM-LSM does not need SST from HYCOM or ice fields from CICE, but if in the future it does need these variables, they would be indirectly passed between coupled NAVGEM and NAVGEM-LSM. Similarly, aerosol loading in the atmosphere (via NAAPS) will influence NAVGEM shortwave and longwave radiation passed to HYCOM and CICE, but there doesn't appear to be a need for direct coupling of NAAPS with any of the other system components but NAVGEM. At this time there is no active research at the Naval Research Laboratory for implementing wave feedback to sea ice, and so there is a one-way arrow between CICE and WW3, not a two-way arrow.

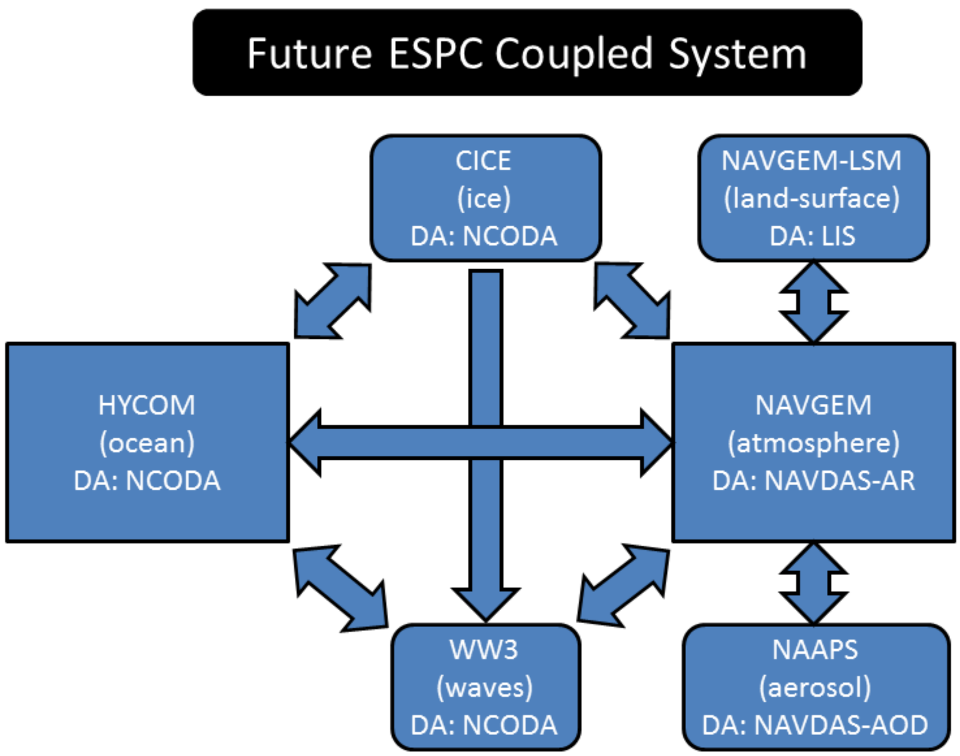

Figure 3: A schematic of the future ESPC coupled system targeted for the Initial Operational Capability in 2018.

Table 1: Projected horizontal and vertical resolutions of the individual ESPC system components at the IOC in 2018.

Forecast	Time Scale, Frequency	Atmosphere NAVGEM	Ocean HYCOM	Ice CICE	Waves WW3	Land-Surface NAVGEM-LSM	Aerosol NAAPS
Deterministic short term	0-10 days, daily	20 km 70 levels (T639L70)	1/25° (4.5 km) 41 layers	1/25° (4.5 km)	1/8° (14 km)	3/16° (21 km)	3/16° (21 km)
Deterministic long term	0-30 days, weekly	20 km 70 levels (T639L70)	1/12° (9 km) 41 layers	1/12° (9 km)	1/4° (28 km)	3/16° (21 km)	3/16° (21 km)
Probabilistic long term	0-90 days, weekly	37 km 50 levels (T359L50)	1/12° (9 km) 41 layers	1/12° (9 km)	1/4° (28 km)	1/3° (37 km)	1/3° (37 km)

The fully coupled system is projected to produce a 10 day short term deterministic forecast once per day, a 30 day long term deterministic forecast once per week, and a 90 day probabilistic forecast once per week. The projected horizontal and vertical resolutions of the system components are shown in Table 1. It is difficult to accurately determine the future computing capacity at the Navy DSRC or FNMOC, but reasonable estimates have been put forth for Navy DSRC in the introduction out through FY16. Estimating the future computing capacity at FNMOC for the FY18 timeframe is not known at this time. However, the design of the system shall be that of a modular system and not infrastructure specific to allow for fluid implementation between, at minimum, Navy DSRC and FNMOC. The forecast length of both the short term and probabilistic forecasts may have to be adjusted to fit within the resources available for operational products at the IOC in 2018. The probabilistic long term forecast may be an independent ensemble run or it may be comprised of prior long term deterministic forecasts. This is still to be determined.

3.1 Data streams

Each component system will have its own input and output streams. Both FNMOC and NAVOCEANO will be responsible for maintaining this data flow.

3.1.1 Input streams

3.1.1.1 Atmospheric input

FNMOC will collect, quality control, and deliver to the operational system atmospheric data in the correct format and in a timely manner, and this includes:

1. *In situ* data
    a. Radiosondes and Pibals
    b. Dropsondes
    c. Driftsonde (Concordiasi)
    d. Land and ship surface observations
    e. Aircraft observations
    f. Synthetic observations
2. Satellite data

a. Surface Winds
    i. Scatterometer, ASCAT and ERS-2
    ii. SSMI/SSMIS
    iii. WindSat
b. Feature Tracked Winds
    i. Geostationary (6 satellites)
    ii. Polar Orbiters (AVHRR and MODIS)
    iii. Combined polar/geo winds (CIMSS)
c. Total Water Vapor
    i. SSMI/SSMIS TVAP
    ii. WindSat TVAP
d. GNSS-RO Bending Angle
    i. GRACE-A
    ii. 5 COSMIC FM1-6 (FM3 has failed)
    iii. 2 GRAS
    iv. Terra and TanDEM SAR-X
    v. CORISS
e. IR Sounding Radiances
    i. IASI
    ii. AIRS
    iii. CrIS
f. MW Sounding Radiances
    i. 6 AMSU-A (Channels 4-14)
    ii. 3 SSMIS (Channels 2-7, 9-11, 22-24)
    iii. 3 MHS (Channels 3-5)
    iv. 1 ATMS (Channels 1-15, 18-22)
g. Ozone retreivals
    i. 3 SBUV/2
    ii. 1 OMPS-Nadir Profiler
    iii. 1 OMPS-Total Column
    iv. GOME-2
h. Aerosol Optical Depth
    i. 2 MODIS (MOD04)
    ii. 4 AVHRR (ACSPO)
    iii. VIIRS
i. Fire Biomass
    i. 2 GOES
    ii. Meteosat
j. Soil Moisture
    i. AMSR-2
    ii. SMOS
k. Ocean Altimeter
    i. Altimeter Sea Surface Height Anomaly (SSHA)
    ii. Altimeter Significant Wave Height (SWH)

3.1.1.2 Oceanographic input

NAVOCEANO will collect, quality control, and deliver to the operational system oceanographic data in the correct format and in a timely manner, and this includes:

1. *In situ* Data

a. Temperature, salinity, profile data from XBT, Argo, TAO moorings, gliders
b. Current observations from HF radar, drifters
c. Optical data from gliders, AUVs
d. Naval Ice Center ice edge

2. Satellite Data
   a. Sea Surface Temperature (SST)
   b. Sea Surface Salinity (SSS)
   c. Altimeter Sea Surface Height Anomaly (SSHA)
   d. Altimeter Significant Wave Height (SWH)
   e. Sea surface color (optical) data
   f. Microwave ice concentration
   g. Satellite-based heat flux estimates

3.1.2 Output streams

In the coupled system, NAVGEM forecast output implies the inclusion of output from NAAPS and the NAVGEM-LSM. The NAVGEM output is required for boundary conditions of COAMPS and WW3. The HYCOM output will include output from CICE and is needed as sea state boundary conditions for NAVGEM. Current NAVGEM output at T359L50 is approximately 0.8 Gb per forecast tau, at T639L70 this would grow to approximately 3 Gb. At 1/25° resolution, HYCOM/CICE output to be passed to NAVGEM will be approximately 0.8 Gb per forecast tau. The standard deterministic atmospheric forecast model will run out to 10 days with output typically written every 3 hours at the earlier times and less frequently either 6 or 12 hours after 5 days of forecast. Thus for the 10-day (30-day) deterministic run, atmosphere and ocean/ice output will total ~228 Gb (~532 Gb). Along with the other forecasting system mentioned above, the output is also fed to various applications such as the Optimum Path Aircraft Routing System (OPARS) and the National Unified Operational Prediction Capability (NUOPC), various Target Acquisition Weapons Systems, and many other critical applications. Finally the NAVGEM ensemble run at T359L50 will have 0.8 Gb of output per ensemble member per tau, resulting in a volume for all members forecasts totaling about 4 Tb. The NAVGEM ensemble outputs are required for CAGIPS maintained at FNMOC. Effective delivery of these model output will need to be insured by the implemented system design.

3.2 The cycling system

In order to provide a comprehensive understanding of the challenges with executing the coupled system across a distributed network, we will address the issues related to which tasks will run at each center as well as some of the issues with job control and file transfer. The computer center chosen to run each task is based on the current projection of resources in the FY18 timeframe. All the forecasts shown in Table 1 will be run on Navy DSRC resources by NAVOCEANO; however, there will be a distribution of the location of where the various Data Assimilation (DA) systems are run. The DA systems for NAVGEM, NAVGEM-LSM, and NAAPS will be executed at FNMOC. These DA systems create the initial conditions for the forecasting system; consequently, the initial conditions for the NAVGEM Global and Ensemble model will be provided to NAVOCEANO by FNMOC.

A cycling system has no starting point, so assuming a previous run of all tasks has completed, the tasks are described below in a numbered order in which they must execute. Tasks with the same number can run concurrently, and the preceding letter indicates either Navy DSRC (N) or FNMOC (F).

N1. NCODA Ocean/Ice and Wave analyses

NAVOCEANO will run the NCODA analysis system on the Navy DSRC for HYCOM and CICE as well as for WW3. The analysis of the ocean, sea-ice and waves are used to initialize the ocean conditions for forecasts from the coupled ocean-atmospheric system. The NCODA analysis also requires 24-hour forecasts from the previous run of the coupled HYCOM/CICE/NAVGEM/NAAPS/NAVGEM-LSM/WW3 for the ocean and atmospheric background, and finally observational data of the ocean over the same 24-hour window. The NCODA Ocean/Ice and Wave analyses are run once daily.

N2. Coupled HYCOM/CICE/NAVGEM/NAAPS/NAVGEM-LSM/WW3 Forecast

The fully coupled HYCOM/CICE/NAVGEM/NAAPS/NAVGEM-LSM/WW3 requires ocean initialization from the NCODA Ocean/Ice and NCODA Wave analysis and the atmospheric initialization from NAVDAS-AR. The forecasts from the coupled ocean-atmospheric system will be used in the subsequent NCODA for both ocean and atmospheric background when analyzing Ocean/Ice and Waves. In addition, distributed incrementally to FNMOC, the ocean and sea ice forecasts are needed for the various atmospheric DA analysis systems run at FNMOC.

F3. NAVDAS-AR Atmospheric, NAVDAS-AOD Aerosol, and LIS Surface analyses

The NAVDAS-AR, NAVDAS-AOD and LIS assimilation system will require ocean surface state, atmospheric forecasts, and a background error estimate. The forecasts are required to cover the assimilation window which is 6-12 hours (shown as 6-hours in Figure 4). Output from a previous NAVGEM ensemble (only 12-hours of forecast are needed) will provide a background error estimate to NAVDAS-AR. NAVOCEANO will provide FNMOC with forecasts of ocean surface state from HYCOM and CICE once daily, and a background error calculated from 12-hour forecasts from the NAVGEM ensemble four times daily. The background atmospheric state will be from a deterministic NAVGEM run at FNMOC. These forecasts and background error estimate are used within the NAVDAS-AR, NAVDAS-AOD and LIS systems along with the various atmospheric observational input data to create initial conditions for long deterministic and probabilistic forecasts of the coupled ocean-atmospheric system described in Table 1.

F4. Coupled NAVGEM/NAAPS/NAVGEM-LSM forecast

FNMOC will run a deterministic NAVGEM 12-hour forecasts (along with NAVGEM-LSM and NAAPS) which are required for the subsequent NAVDAS-AR assimilation cycle four times daily. If computational resources are adequate in the FY18 timeframe, longer deterministic forecasts and an ensemble system may also be run in addition at FNMOC.

N4. NAVGEM ensemble forecast

NAVOCEANO will run the NAVGEM ensemble four times daily producing the background error estimates for the subsequent NAVDAS-AR run and long forecasts for systems such as NUOPC and CAGIPS. Further, the ensemble will be used to initialize the atmospheric state in the NCODA Wave analysis for the WW3 run at FNMOC.

F5. NCODA Wave analysis

The NCODA Wave analysis system will use a forecast of ocean state from the fully coupled ocean-atmospheric system, atmospheric state from the NAVGEM ensemble, and ocean wave height observational data to produce a wave analysis and subsequent forecast for distribution by FNMOC four times daily. This is not to be confused with the NCODA Wave analysis run at NAVOCEANO to initialize the waves for the long forecast by the coupled ocean-atmospheric system which is run once daily.

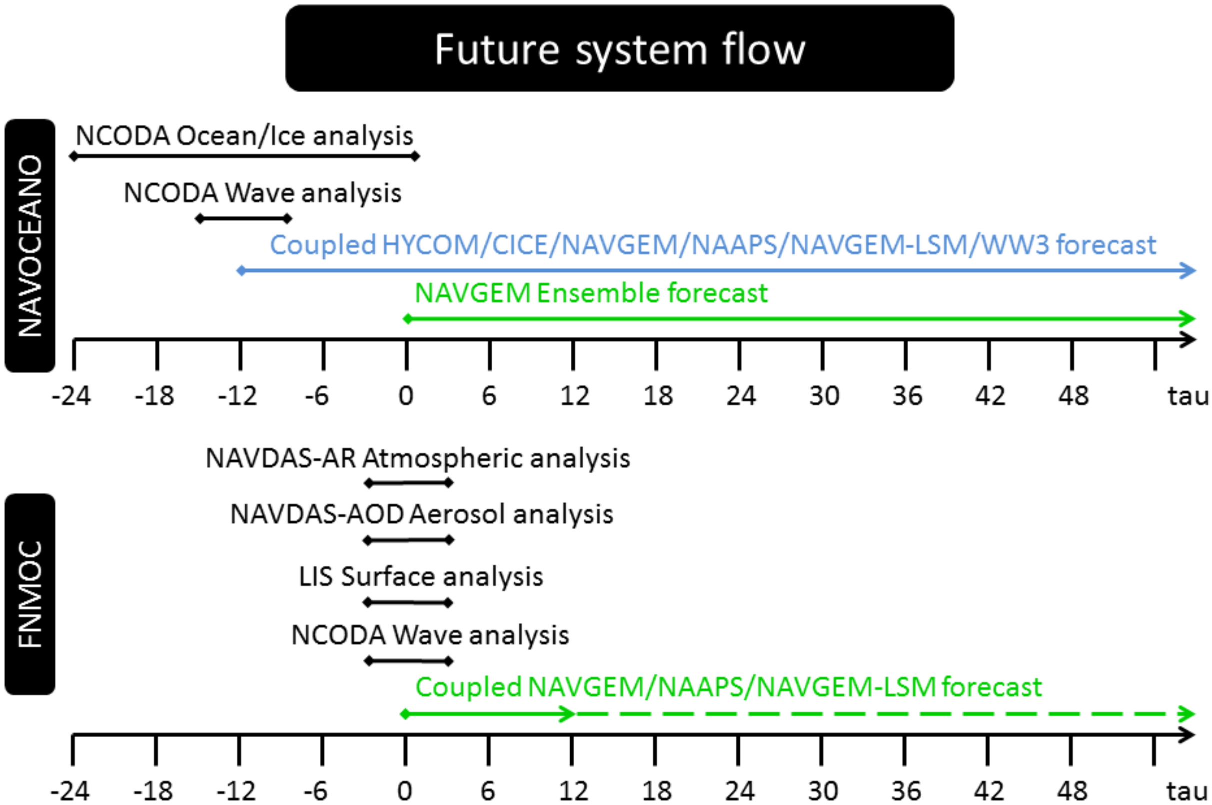

Figure 4: A schematic of the tasks and their distribution between Navy DSRC (executed by NAVOCEANO) and FNMOC.

3.2.1 Issues

3.2.1.1 Transfer of atmospheric data to NAVOCEANO

Transfer of the atmospheric observational data from FNMOC to NAVOCEANO is not recommended. The atmospheric input data streams are of a much higher volume and are highly more time critical than the oceanographic counterparts because the atmospheric timescales are on average much shorter. As of 2013, the atmospheric assimilation systems process a continuous data stream of 5 Gb per update cycle (6 hour window) and by 2018 we would expect them to grow to a minimum of 40 Gb. Further, by the 2025 time frame these streams are expected to exceed 100 Gb per assimilation window. FNMOC has an existing Bulk File Transfer (BFT) subsystem which, together with custom Distributed Processing System (DPS) software, supports the automatic transfer, through the FNMOC firewall/DMZ, of data files into and out of the FNMOC protected architecture. To reiterate, these are continuous and time critical data streams, and the infrastructure for ingestion (BFT and DPS), as well as satellite dishes and the appropriate agreements to receive and provide data with the various other data distributors exist only at FNMOC. Due to these considerations, it will be most efficient to do the atmospheric assimilation at FNMOC and only move NAVGEM history files and initial conditions (as of 2013 ~0.8 Gb) to Navy DSRC, where NAVOCEANO will be responsible for running the longer forecasts of NAVGEM and the NAVGEM ensembles.

3.2.1.2 Transfer of model data to FNMOC

The requirement to move large amounts of data between FNMOC and NAVOCEANO, in a very short period of time and within required Information Assurance (IA) constraints, is the most challenging aspect of the ESPC project. The transfer of the ocean surface state from the coupled ocean-atmospheric system to FNMOC is not deemed to be the largest volume as it is only the ocean/ice surface and currently estimated at ~0.8 Gb per forecast tau. The volume which will strain resources is that of the NAVGEM ensemble which is required for CAGIPS, and the WW3 run at FNMOC. The volume is expected to be roughly 80 Gb per forecast tau for all ensemble members. A possible solution would be a Defense Research and Engineering Network (DREN) III upgrade to allow FNMOC Service Delivery Point bandwidth to be increased to OC-24 (1.2 Gbs), doubling the potential throughput. It has been suggested by the Navy DSRC Director that the best solution would be a more significant upgrade to an OC-48 (2.5 Gbs) circuit and this could be accomplished at minimal additional cost.

3.2.1.3 Distributed job control/scheduling

Based on information provided by the HPCMO, **machine-to-machine communication between a DSRC and any outside system allows for only one action/command**: secure copy (scp). This would allow either FNMOC or NAVOCEANO to establish control of ESPC tasks using **a file-based messaging paradigm**, using CRON and the scp command to send “messages” between the FNMOC and NAVOCEANO. The CRON timer would run at a high refresh (2 seconds) continually looking for these messages and executing. This is a massive backwards step in job scheduling and control which would best be served by putting heads together and finding a truly realistic solution within the IA constraints.

3.2.1.4 Future of computing infrastructure

Estimates of the Navy DSRC computing infrastructure are given in the introduction; however, those of FNMOC are not conclusive for FY18 at the writing of this report. Upgrades to the FNMOC or further changes to the Navy DSRC computing infrastructure would allow for rebalancing of tasks. The design of the coupled system will continue to take a modular approach with the idea of a fluid implementation of tasks between the centers which will maximize efficiency and keep data transfers to a minimum. A larger computing capability at FNMOC would allow for reduction of the largest volume of data transfer which is the running of the NAVGEM atmospheric ensemble. If in the future an upgrade to the FNMOC infrastructure is foreseen, this would remove the NAVGEM ensemble output, approximately 4 Tb every six-hours, from the data transfer and greatly alleviate the burden allowing for more stable transfer of the initial conditions and the forecasts from the global coupled systems between the Navy DSRC and FNMOC.

4.0 Concluding remarks

A general outline of the ESPC coupled atmosphere/ocean/ice/wave/land prediction system is proposed for the Initial Operational Capability targeted for 2018. A description of how it will cycle at both FNMOC and NAVOCEANO is included, although the specifics of how the distributed job control will function are still to be determined as the system becomes more mature. A potential issue with regard to the transfer of model output between the two centers has been identified and must be addressed in the upcoming years.

5.0 Acknowledgements

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6.0 References

Bleck, R., 2002: An oceanic general circulation model framed in hybrid isopycnic-Cartesian coordinates. *Ocean Modelling*, 4, 55-88.

Bloom, S.C., L.L. Takacs, A.M. Da Silva, and D. Ledvina, 1996: Data assimilation using incremental analysis updates. *Mon. Weather Rev.*, 124, 1256-1271.

Booij, N., R. C. Ris, and L.H. Holthuijsen, 1999: A Third-Generation Wave Model for Coastal Region: 1. Model Description and Validation, *J. Geophys. Res*., 104(C4), 7649-7666.

Chassignet, E.P., L.T. Smith, G.R. Halliwell and R. Bleck, 2003: North Atlantic simulations with the HYbrid Coordinate Ocean Model (HYCOM): Impact of the vertical coordinate choice, reference pressure, and thermobaricity. *J. Phys. Oceanogr*., 33(12), 2504-2526.

Chawla, A., H.L. Tolman, J.L. Janson, E.-M. Devaliere, V.M. Gerald, 2009: Validation of a Multi-Grid WAVEWATCH III™ Modeling System, MMAB Contribution no. 281, online. http://polar.ncep.noaa.gov/mmab/papers/tn281/multi_hindanalysis.pdf.

Chua, B., L. Xu, T. Rosmond, and E. Zaron, 2009: Preconditioning representer-based variational data assimilation systems: application to NAVDAS-AR. *Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications,* Springer-Verlag, 493 pp.

Cummings, J.A., 2005: Operational multivariate ocean data assimilation. *Quart. J. Royal Met. Soc*., 131, 3583-3604.

Cummings, J.A., and O.M. Smedstad, 2013: Variational data assimilation for the global ocean. S.K. Park and L. Xu (eds.), *Data Assimilation for Atmospheric, Oceanic and Hydrological Applications (Vol. II)*, DOI 10.1007/978-3-642-35088-7_13, Springer-Verlag Berlin Heidelberg.

Dee, D., 2004: Variational bias correction of radiance data in the ECMWF system. In *Proceedings of the ECMWF workshop on assimilation of high spectral resolution sounders in NWP*, 28 June-1 July 2004, Reading, UK, pp. 97-112.

Dykes, J. D. and W.E. Rogers, 2013: Implementation of the Multiple Grid System of WAVEWATCH III at NAVOCEANO. *NRL Memorandum Report: NRL/MR/7320-12-9494*, 19 pp.

Halliwell, G. R., 2004: Evaluation of vertical coordinate and vertical mixing algorithms in the HYbrid Coordinate Ocean Model (HYCOM), *Ocean Modelling*, 7(3–4), 285–322.

Hill, C., C. DeLuca, V. Balaji, M. Suarez, A. da Silva, 2004: The Architecture of the Earth System Modeling Framework. *Computing in Science and Engineering*, Vol. 6, pp 18-28.

Hodur, R.M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmopheric Mesoscale Prediction System (COAMPS). *Mon. Wea. Rev*., **125**, 1414-1430.

Hunke, E.C. and W. Lipscomb, 2008: CICE: The Los Alamos sea ice model, documentation and software user's manual, version 4.0. *Tech. Rep. LA-CC-06-012*, Los Alamos National Laboratory, Los Alamos, NM. (http://climate.lanl.gov/models/cice/index.htm).

Hyer, E. J., J. S. Reid, and J. Zhang (2011), An over-land aerosol optical depth data set for data assimilation by filtering, correction, and aggregation of MODIS Collection 5 optical depth retrievals, *Atmospheric Measurement Techniques*, 4, 379-408, doi: 10.5194/amt-4-379-2011.

Jensen, R. E., P. A. Wittmann, and J. D. Dykes, 2002: Global and Regional Wave Modeling Activities: *Oceanography*, Vol 15, No. 1, 2002, pp. 57-66.

Metzger, E.J., H.E. Hurlburt, X.Xu, J.F. Shriver, A.L. Gordon, J. Sprintall, R.D. Susanto and H.M. van Aken, 2010a: Simulated and observed circulation in the Indonesian Seas: 1/12◦ global HYCOM and the INSTANT observations. *Dyn. Oceans Atmos.*, 50, 275-300, doi:10.1016/j.dynatmoce.2010.04.002.

Metzger, E.J., O.M. Smedstad, P.G. Thoppil, H.E. Hurlburt, A.J. Wallcraft, D.S. Franklin, J.F. Shriver and L.F. Smedstad, 2008: Validation Test Report for the Global Ocean Prediction System V3.0 - 1/12º HYCOM/NCODA: Phase I. *NRL Memo. Report*, NRL/MR/7320--08-9148. (Available at http://www7320.nrlssc.navy.mil/pubs.php.)

Metzger, E.J., O.M. Smedstad, P.G. Thoppil, H.E. Hurlburt, D.S. Franklin, G. Peggion, J.F. Shriver, T.L. Townsend and A.J. Wallcraft, 2010b: Validation Test Report for the Global Ocean Forecast System V3.0 - 1/12º HYCOM/NCODA: Phase II. *NRL Memo. Report*, NRL/MR/7320--10-9236. (Available at http://www7320.nrlssc.navy.mil/pubs.php.)

Mitchell, K., M. Ek, V. Wong, D. Lohmann, V. Koren, J. Schaake, Q. Duan, G. Gayno, B. Moore, P. Grunmann, D. Tarpley, B. Ramsay, F. Chen, J. Kim, H.L. Pan, Y. Lin, C. Marshall, L. Mahrt, T. Meyers, and P. Ruscher, 2005: The Community Noah Land-Surface Model, User's Guide Version 2.7.1. (Available at ftp://ftp.emc.ncep.noaa.gov/mmb/gcp/ldas/noahlsm/ver_2.7.1).

Pincus, R., H.W. Barker, and J.-J. Morcrette, 2003: A fast, flexible, approximate technique for computing radiative transfer in inhomogeneous clouds. *J. Geophys. Res*., 108(D), 4376, doi:10.1029/2002JD003322

Reid, J. S., et al. (2009), Global Monitoring and Forecasting of Biomass-Burning Smoke: Description of and Lessons from the Fire Locating and Modeling of Burning Emissions (FLAMBE) Program, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 2(3), 144-162.

Ritchie, H. 1991: Application of the semi-Lagrangian method to a multilevel spectral primitive equation model. *Q. J. R. Meteorol. Soc*., 117, 91-106.

Rogers, W. E., and T. J. Campbell, 2009: Implementation of Curvilinear Coordinate System in the WAVEWATCH-III Model. *NRL Memorandum Report: NRL/MR/7320-09-9193*, 42 pp.

Rogers, W. E., J. D. Dykes, D. Wang, S.N. Carroll, and K. Watson, 2012: Validation Test Report for WAVEWATCH III. *NRL Memorandum Report: NRL/MR/7320-12-9425*, 73 pp.

Tolman, T.L., B. Balasubtaminiyan, L. D. Burroughs, D. V. Chalikov, Y. Y. Chao, H. S. Chen, and V. M. Gerald, 2002: Development and implementation of wind generated ocean surface wave models at NCEP, *Wea, and Forecasting*, Vol. 17, April 2002, 311-333.

Tolman, H.L., 2007: Toward a third release of WAVEWATCH III; a multi-grid model version, Tech. Note 251, NOAA/NWS/NCEP/MMAB, 12 pp.

Wittmann, P.A., 2002: Implementation of WAVEWATCH III at Fleet Numerical Meteorology and Oceanography Center. *Conf. Proceedings: MTS/IEEE: Conference and Exposition*. Nov 5-8, 2001 Honolulu, HI, 1474-1479.

Zhang, J. L., and J. S. Reid (2006), MODIS aerosol product analysis for data assimilation: Assessment of over-ocean level 2 aerosol optical thickness retrievals, *J. Geophys. Res.-Atmos*., 111(D22), D22207.

Zhang, J. L., J. S. Reid, and B. N. Holben (2005), An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products, *Geophys. Res. Lett.*, 32(15), L15803.

Zhang, J. L., J. S. Reid, D. L. Westphal, N. L. Baker, and E. J. Hyer (2008), A system for operational aerosol optical depth data assimilation over global oceans, *J. Geophys. Res.-Atmos.*, 113(D10), D10208.

Zhao, Q. Y., and F. H. Carr, 1997: A prognostic cloud scheme for operational NWP models. *Mon. Wea. Rev*., 125, 1931-1953.